Low Level RF Workshop 2013

Application of Active Disturbance Rejection Control in Superconducting Radio Frequency Cavities

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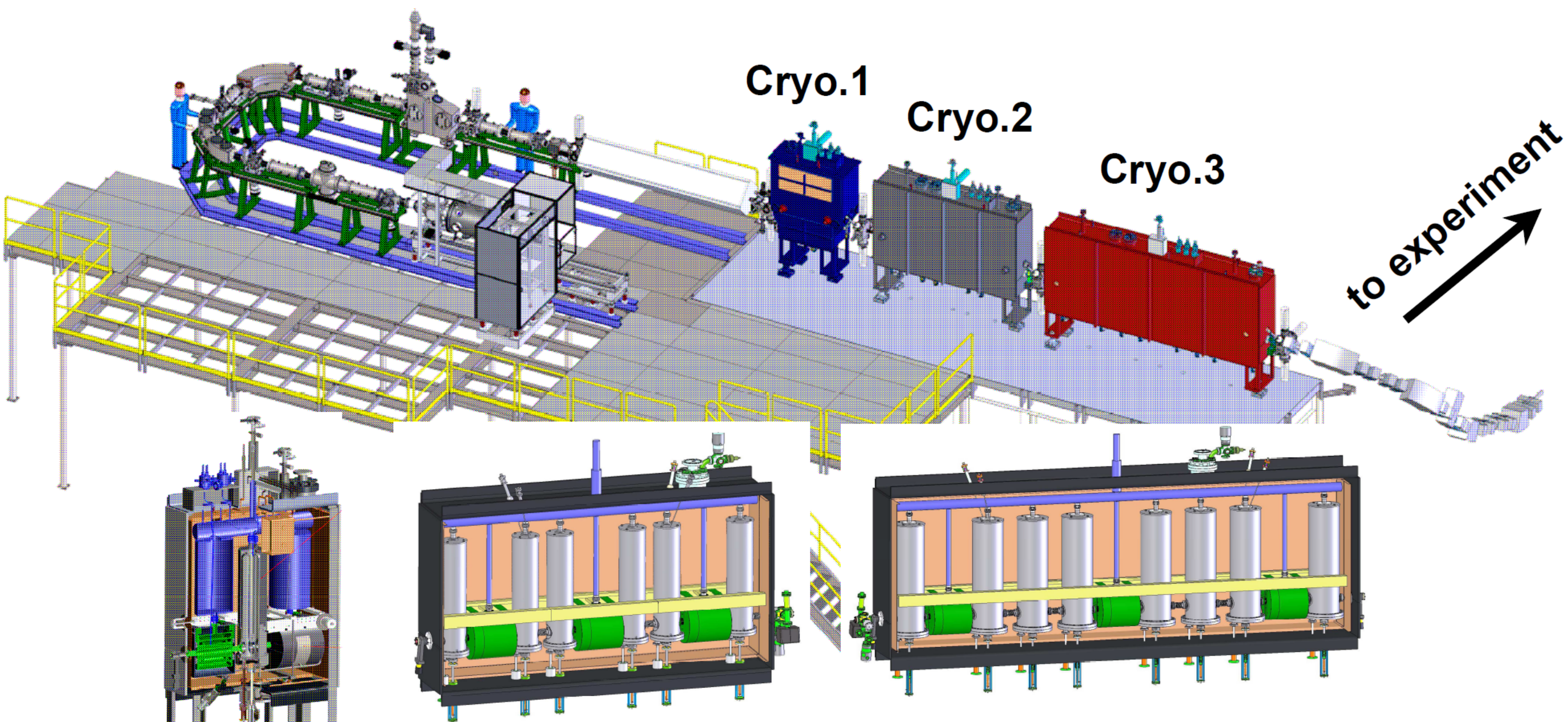
Outline

- Previous Results on Microphonics Mitigation
- More on Active Disturbance Rejection Control (ADRC)
- ADRC Applications at FRIB/NSCL
  - Beam Loading
  - FPGA Implementation
  - Tuner Control
  - ReA3 Vibration Test

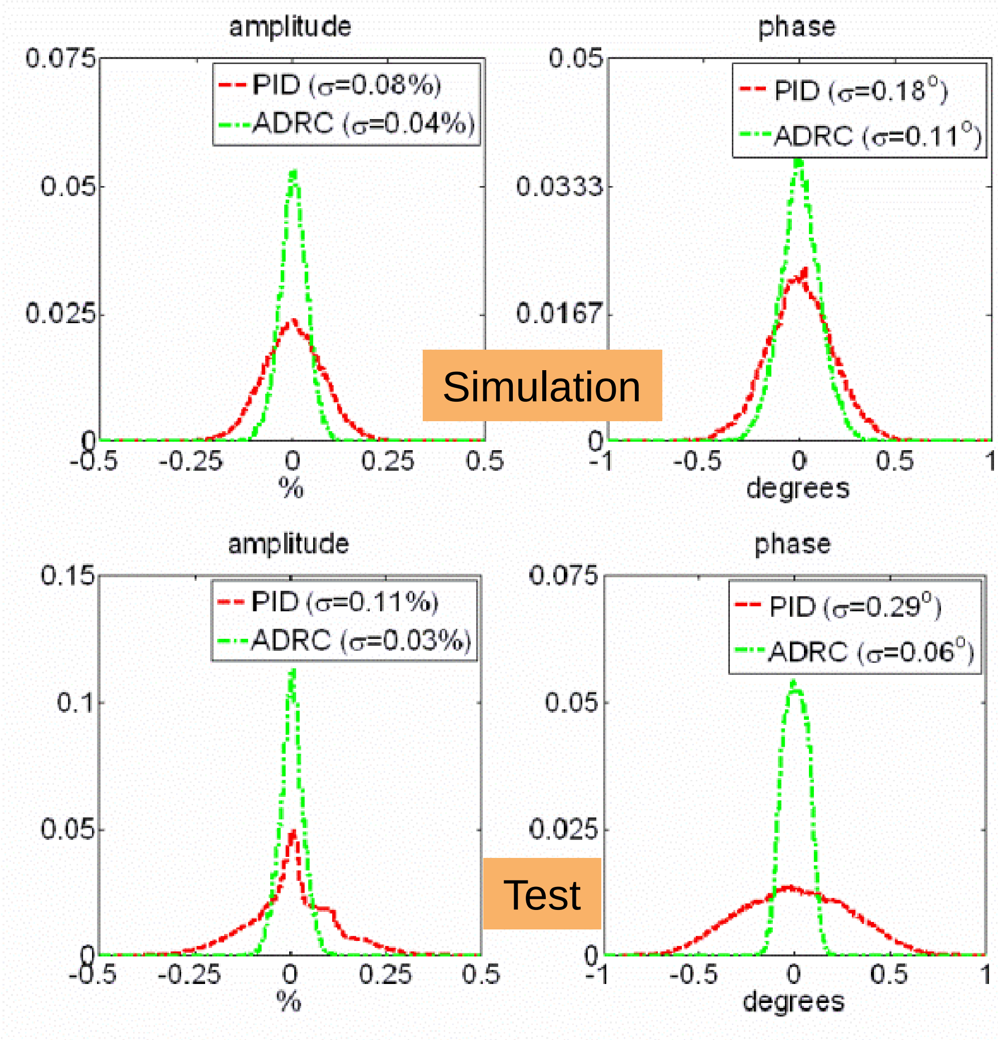
First Application of ADRC in SFR Cavities

- Application of ADRC at NSCL
  - Spring 2010
  - Narrow bandwidth and sensitive to vibrations
  - ReA3 is on the balcony and the vibration is severe



Previous Results

- Demonstrated the effectiveness of ADRC [Vincent, 2011]
  - Two times improvement in simulation (top)
  - Four times improvement in tests (bottom)
  - Running on ReA3 since Jan. 2011



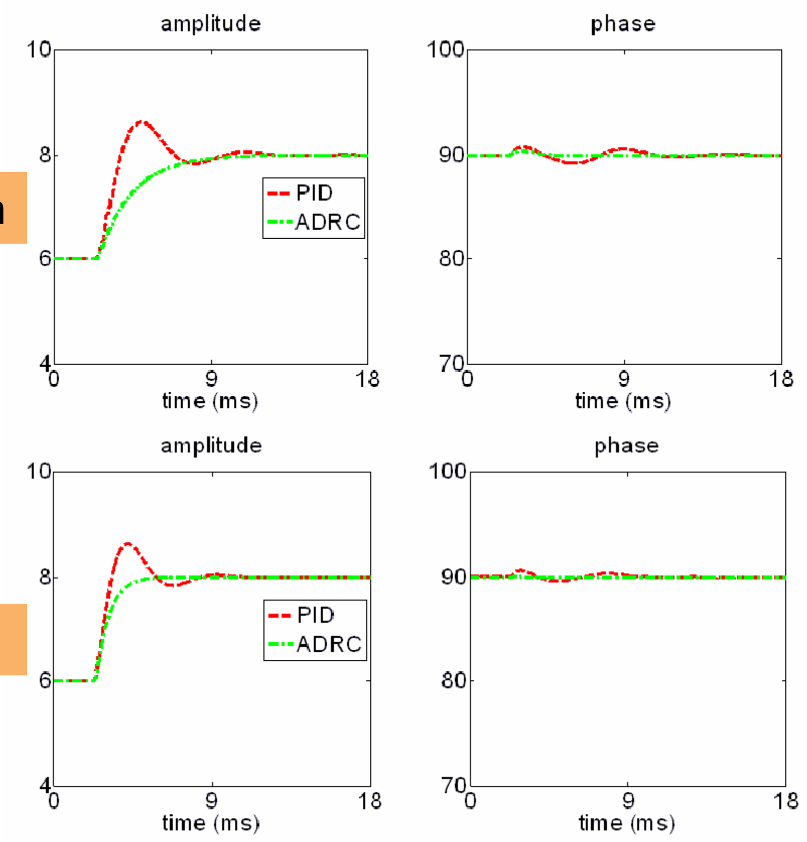
Better Decoupling

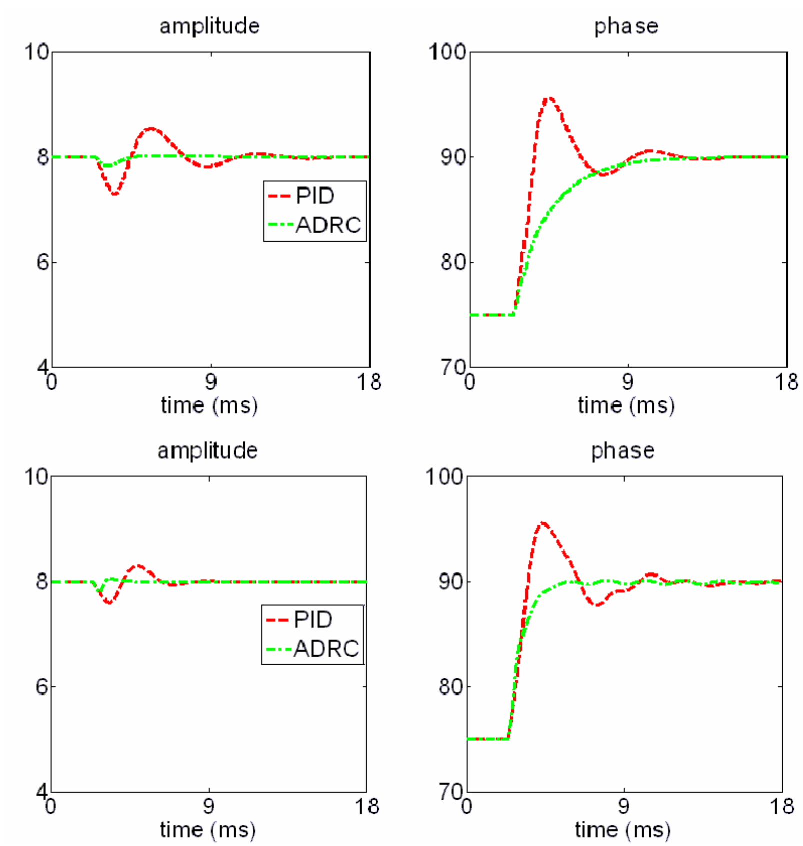
Amplitude Set-point Change

Phase Set-point Change

Simulation

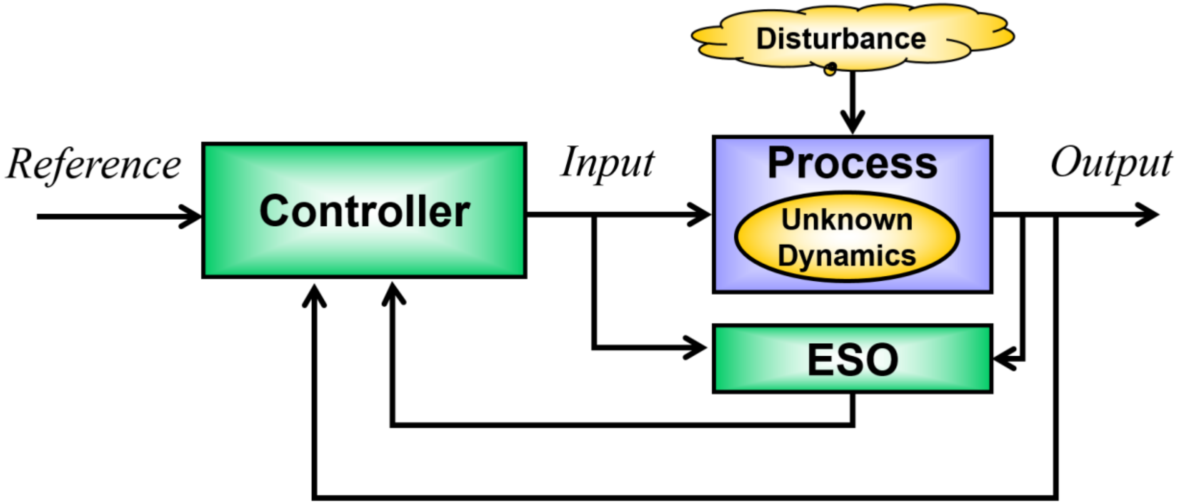
Test





Active Disturbance Rejection Control

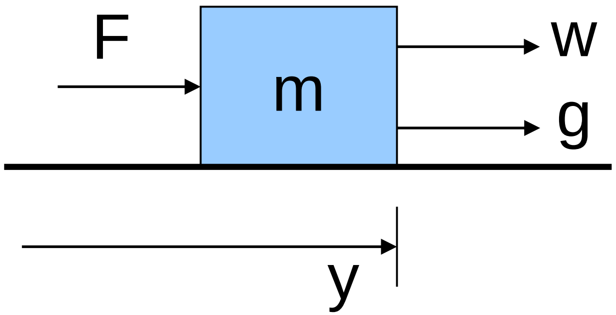
- Proposed by Prof. Han in 1998 [Han 2009]
  - Treat external disturbance and system uncertainty as the *total disturbance*
  - Estimation the total disturbance using an extended state observer (ESO)
  - Cancel it in the controller



- Other Similar Methods
  - Unknown Input Observer
  - Disturbance Observer
  - Perturbation Observer

(only deal with external disturbance)

ADRC Formulation - A Simple Example



$$m\ddot{y} = F + \underbrace{g(y,\dot{y},t)}_{\text{Internal Uncertainty}} + \underbrace{w(t)}_{\text{External Disturbance}}$$

$$b = 1/m \qquad u = F$$

$$f(y,\dot{y},w,t) = \big(g(y,\dot{y},t) + w(t)\big)/b$$

$$\ddot{y} = bu + \underbrace{f(y,\dot{y},w,t)}_{\text{Total Disturbance}}$$

$$u = \left(-\hat{f} + u_0\right)/b$$

$$\ddot{y} = u_0 + \left(f - \hat{f}\right) \approx u_0$$

Disturbance Cancellation

$$u_0 = k_p e + k_d \dot{e}$$

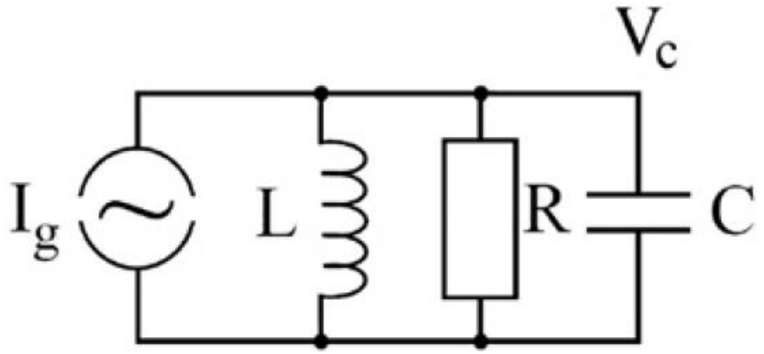
Simple Controller

SRF Cavity Model

- Parallel RLC Circuit Model

$$\frac{d^2\overrightarrow{V}_c}{dt^2}+\frac{\omega_0}{Q}\frac{d\overrightarrow{V}_c}{dt}+\omega_0^2\overrightarrow{V}_c=\frac{R\omega_0}{Q}\frac{d\overrightarrow{I}_g}{dt}$$

$$\omega_0=1/\sqrt{LC} \qquad Q=R\sqrt{C/L}$$



- Approximation

$$\dot{V}_{cI}+\omega_{1/2}V_{cI}+\Delta\omega V_{cQ}=\omega_{1/2}V_{gI}$$
$$\dot{V}_{cQ}+\omega_{1/2}V_{cQ}-\Delta\omega V_{cI}=\omega_{1/2}V_{gQ}$$

$$\begin{cases} I=A\cos P \\ Q=A\sin P \end{cases}$$

ADRC Design for SRF Cavity

$$\dot{V}_{cI} + \omega_{1/2} V_{cI} + \Delta\omega V_{cQ} = \omega_{1/2} V_{gI}$$

$$\dot{V}_{cQ} + \omega_{1/2} V_{cQ} - \Delta\omega V_{cI} = \omega_{1/2} V_{gQ}$$

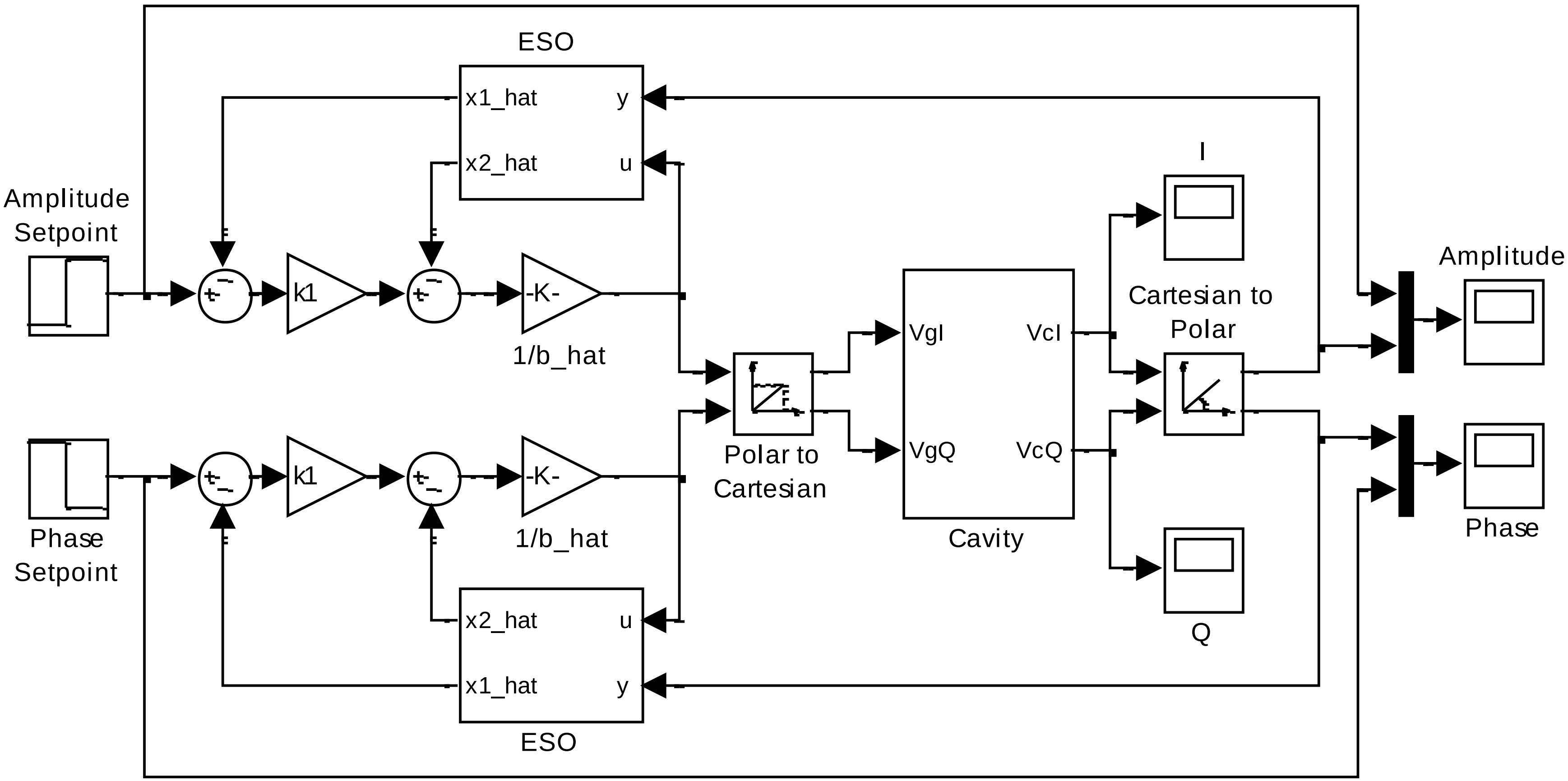
- Algorithm
  - System $\dot{y} = f(y, w, t) + bu$
  - Observer
    - $\dot{\hat{x}}_1 = \hat{x}_2 + \hat{b}u + l_1 (y - \hat{x}_1)$ Estimation of y
    - $\dot{\hat{x}}_2 = l_2 (y - \hat{x}_1)$ Estimation of f
  - Controller $u = (k_1 (r - y) - \hat{x}_2) / \hat{b}$

Disturbances in SRF Cavities

- Microphonics
  - Ground vibration;
  - Pumps: Helium pump, vacuum pump, etc.
- Lorentz Force
- Beam Dynamics
  - Beam loading;
  - Beam current variation.
- Others
  - Hysteresis in piezo tuner;
  - Non-linearity in solid state amplifier.

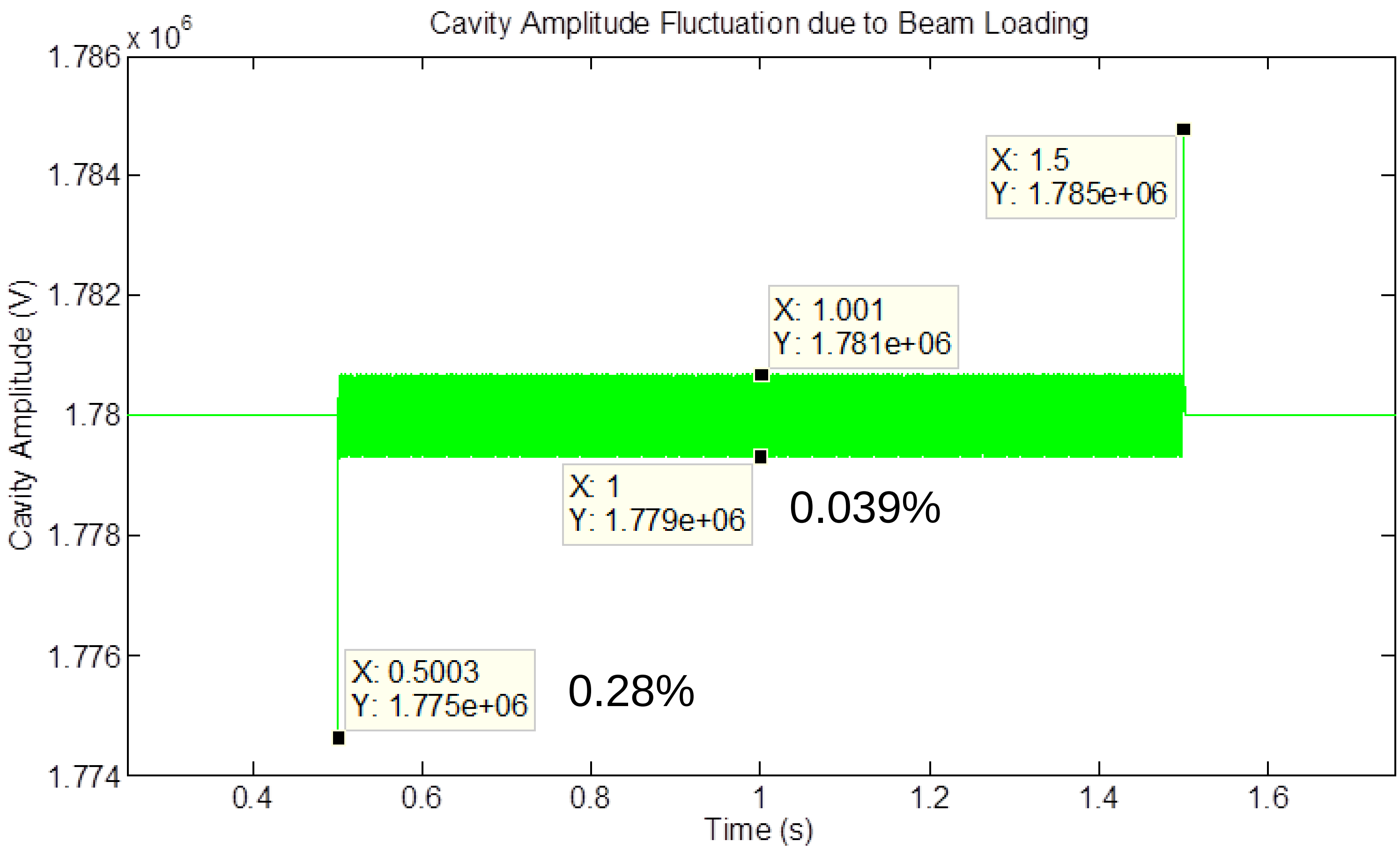
Beam Loading [Zheng 2012]

- Simulation Model



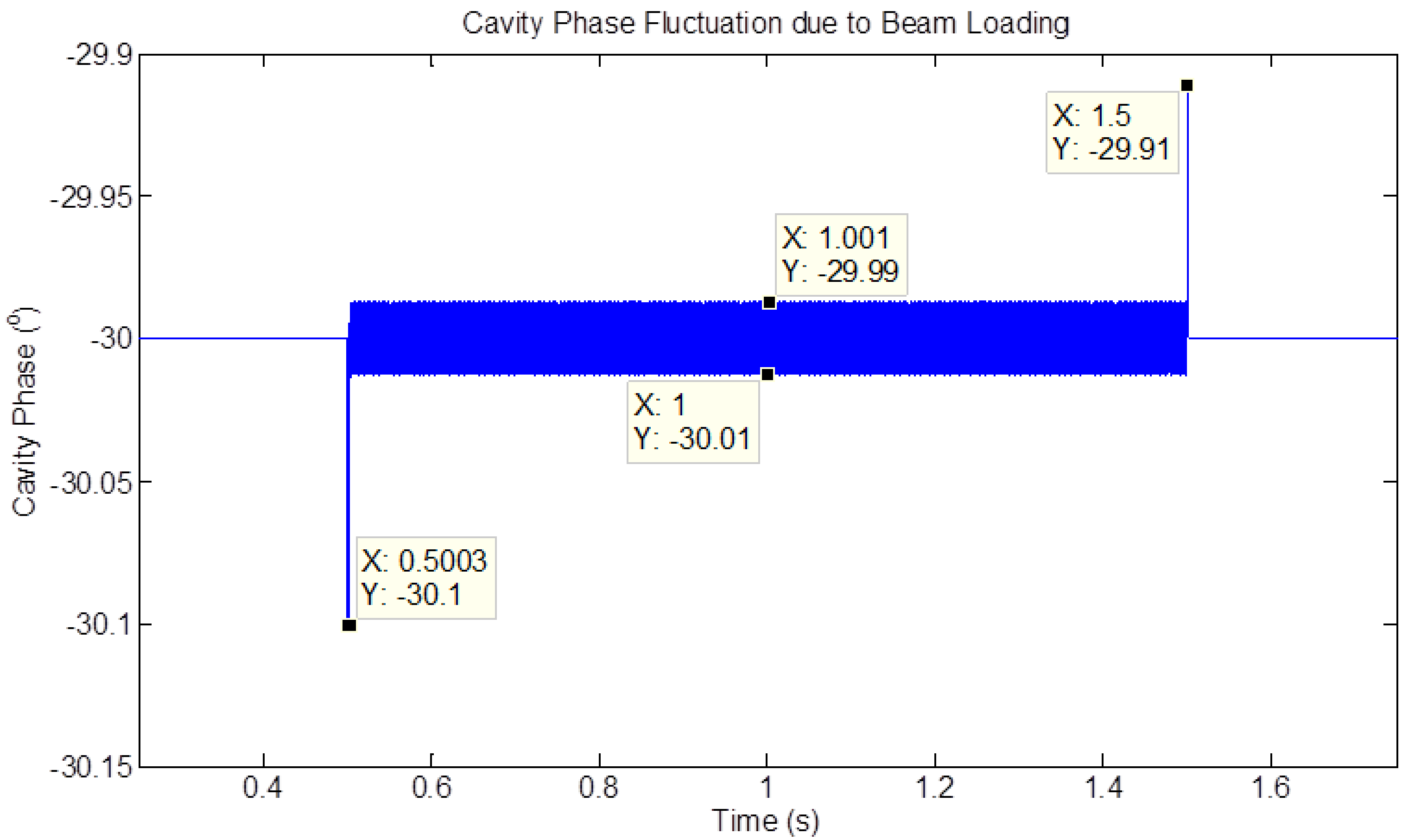
Results under Beam Loading

- Amplitude Response



Results under Beam Loading

- Phase Response

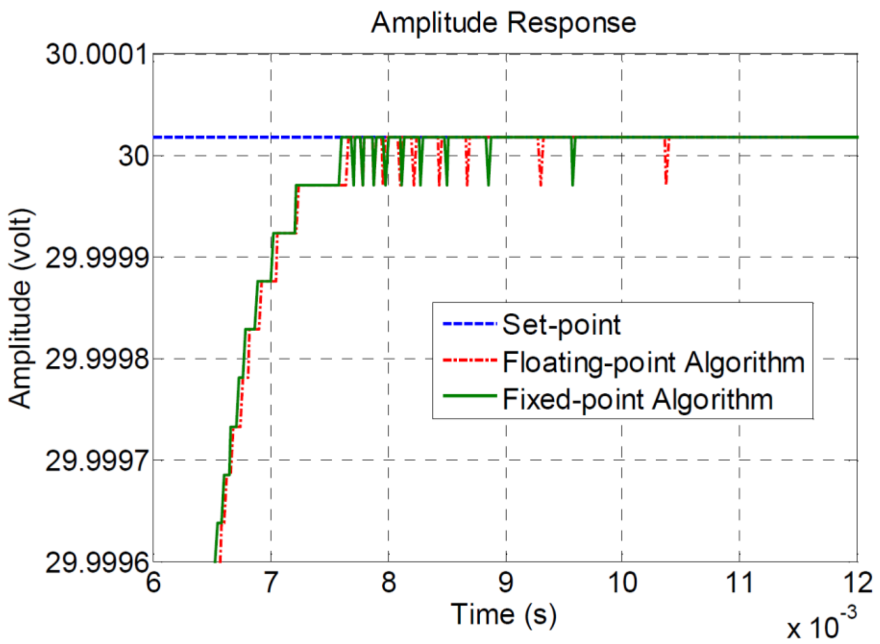


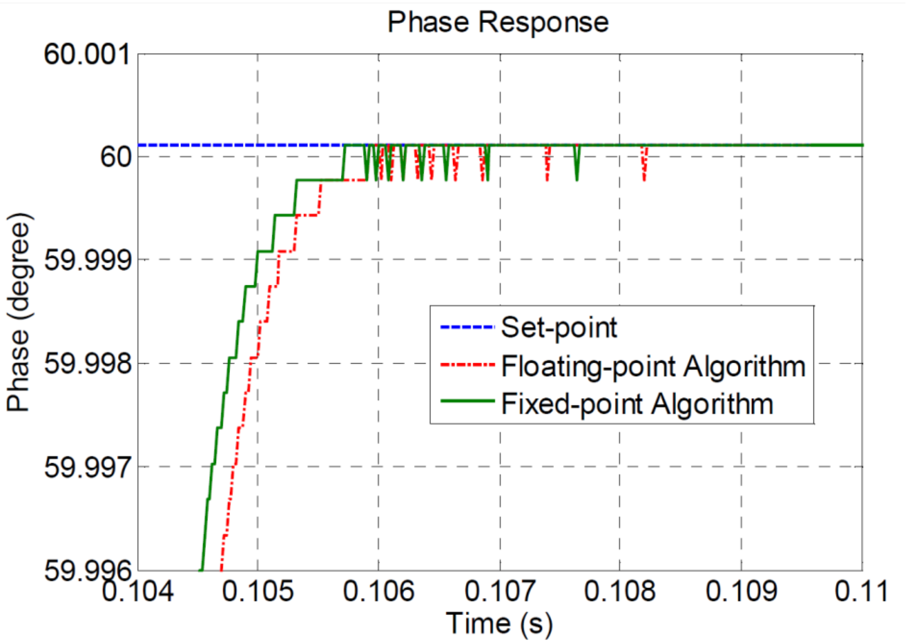
FPGA Implementation [Zhao 2013]

- To increase the sampling rate
  - Potential performance improvement
    - » Observer bandwidth can be further increased;
  - Expands the working range of the SEL
    - » 1/12 of the sampling rate [Zhao 2011];
    - » Currently around 4 KHz (50 KHz in DSP);
- No processor planned in LLRF controller (long term)
  - ADRC algorithm has to go into the firmware;

Simulation Results

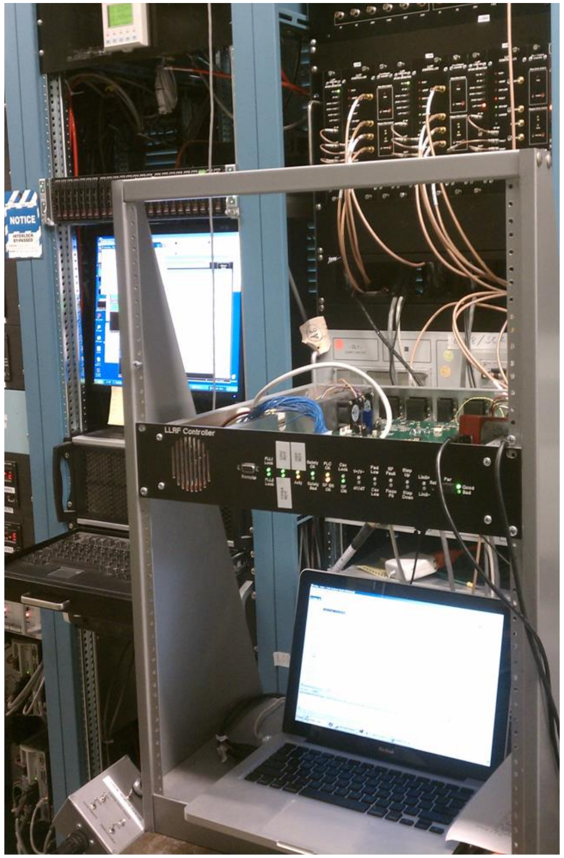
- A Comparison between Fixed-point and Floating-point Algorithms





Hardware Test Verification

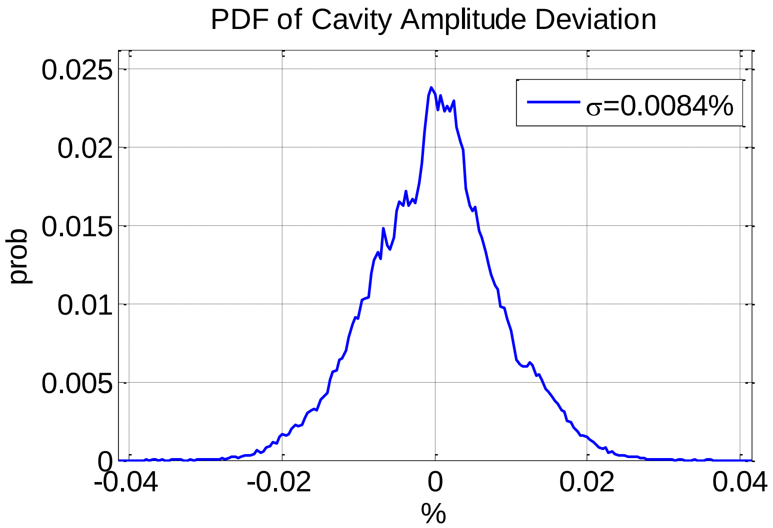
- LLRF Controller PED 1
- ReA3 L088, Dec. 2012

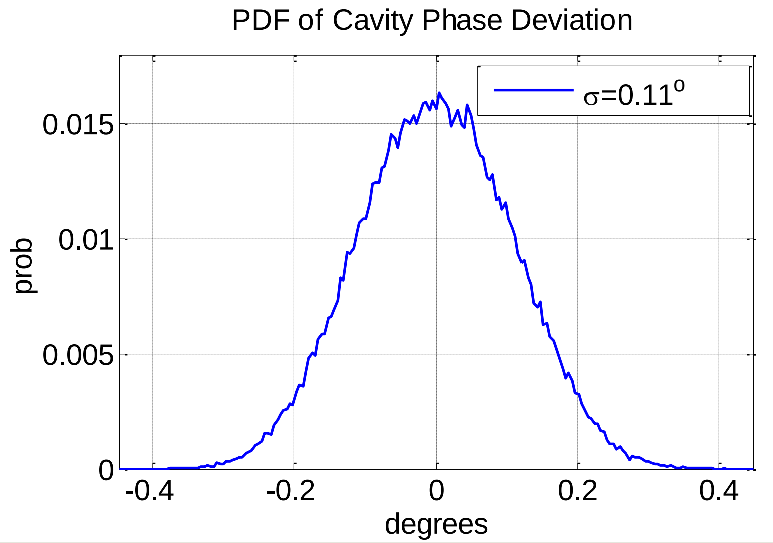


FRIB Specs:

Amplitude (RMS) : <0.25%

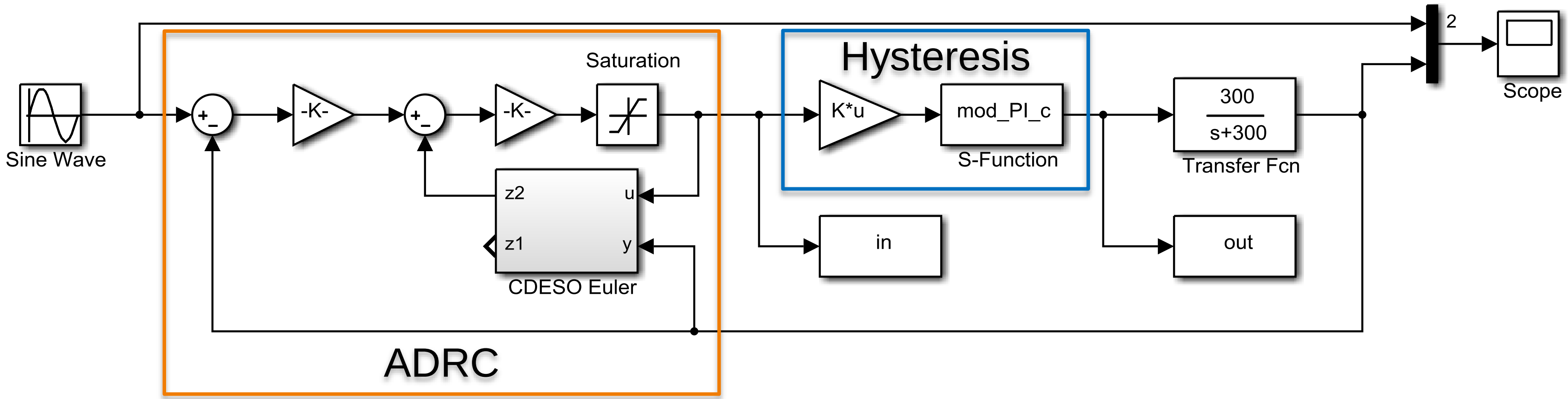
Phase (RMS): <0.25 degrees



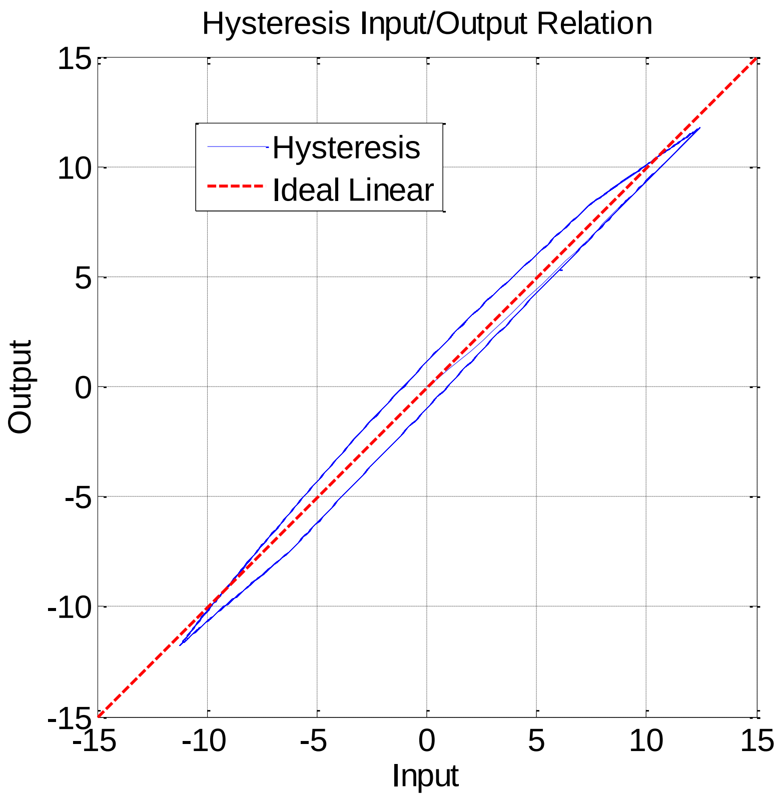


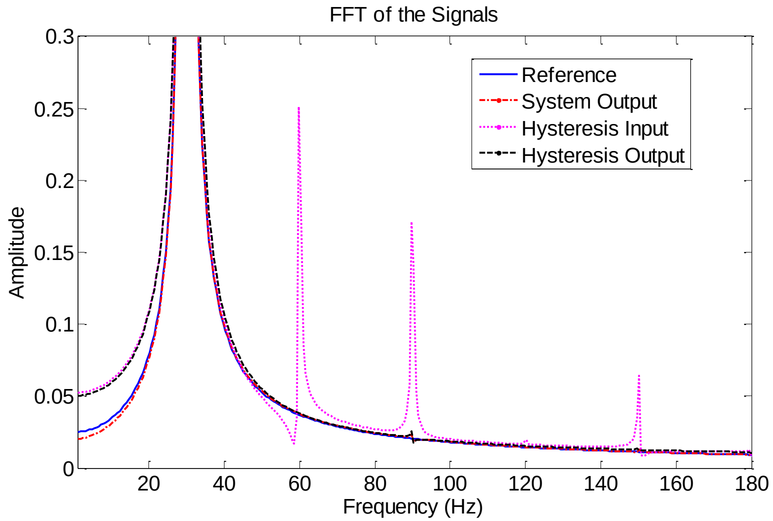
Tuner Control

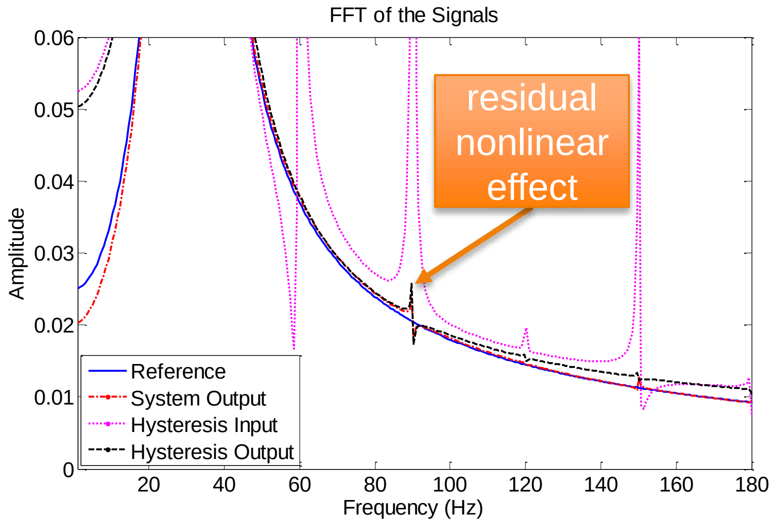
- Fast Piezoelectric Tuner
  - Hysteresis compensation [Goforth 2012]



Simulation Results

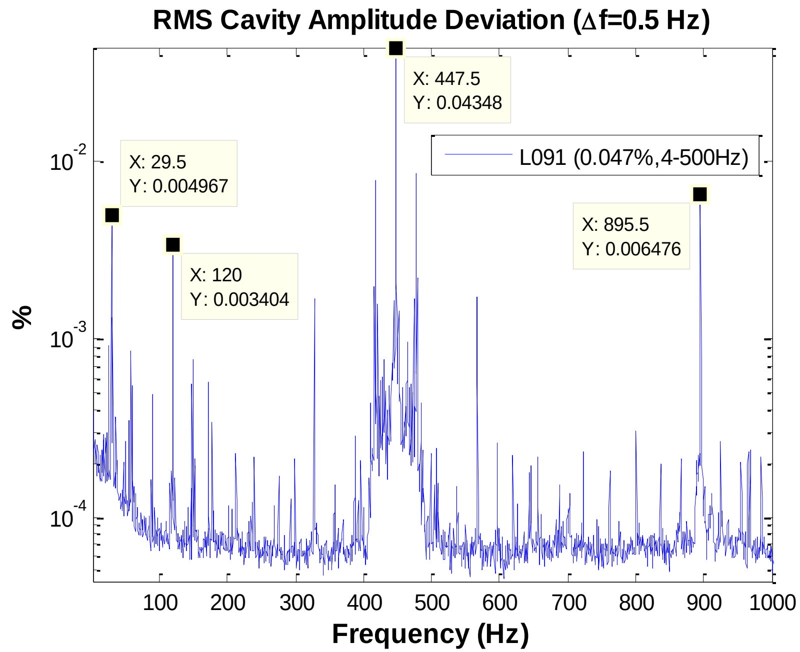


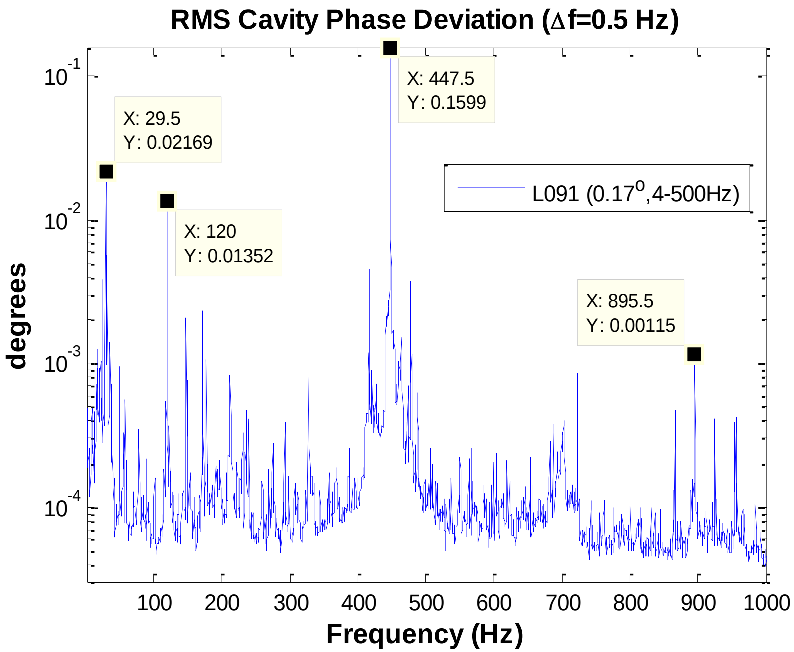




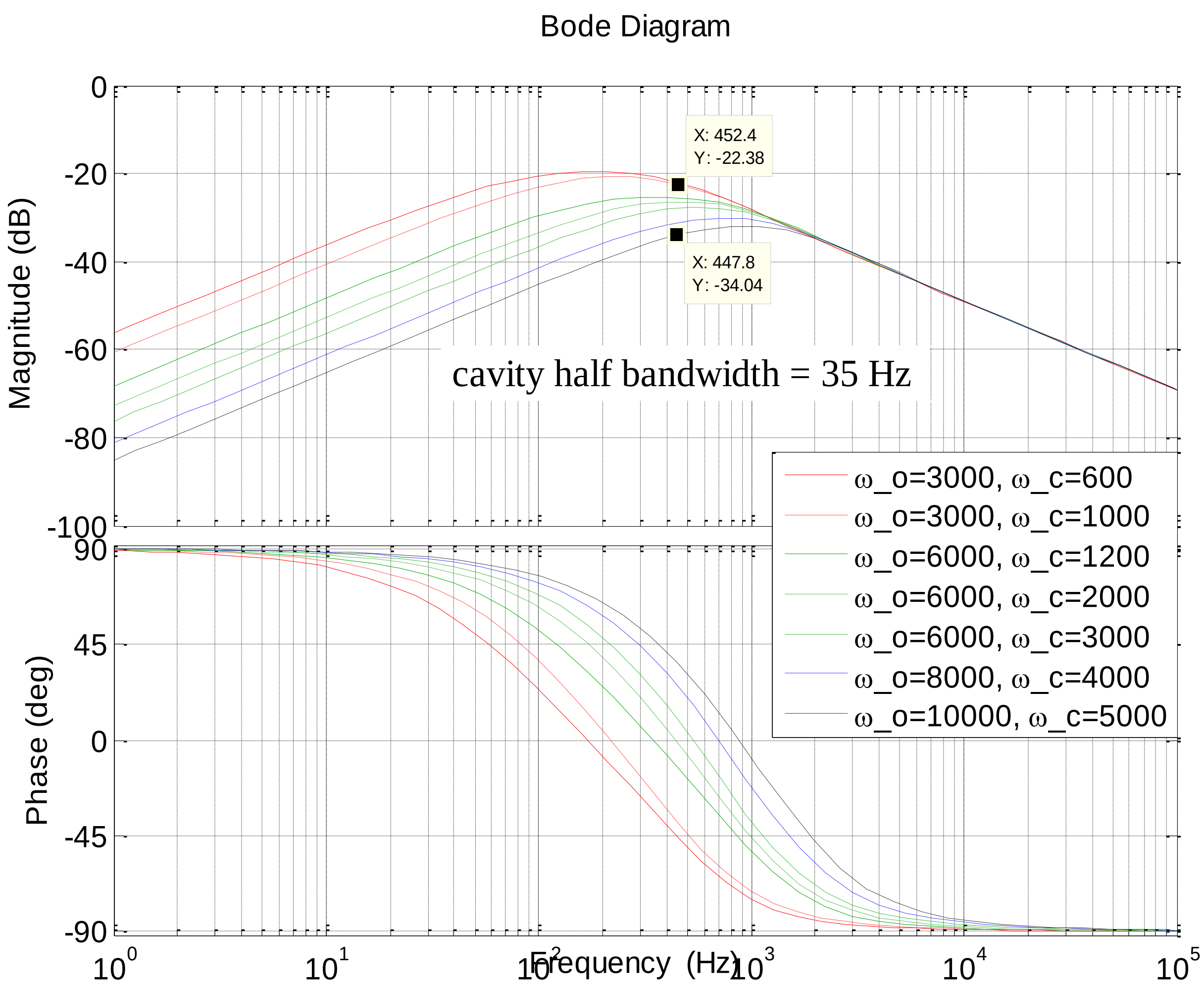
ReA3 Vibration Test

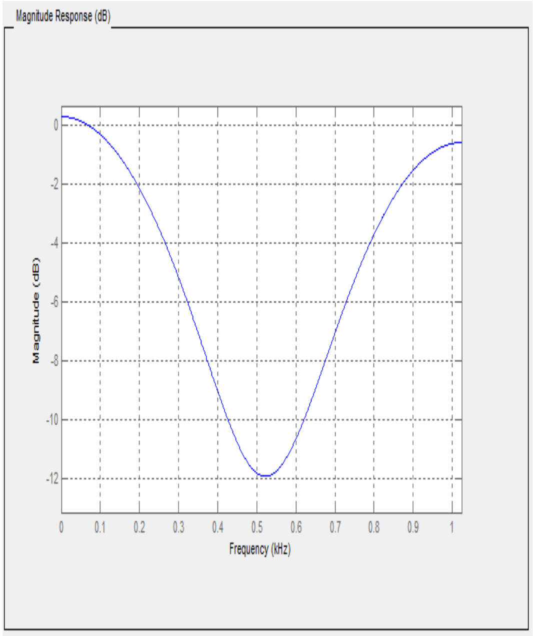
- Original Measurement



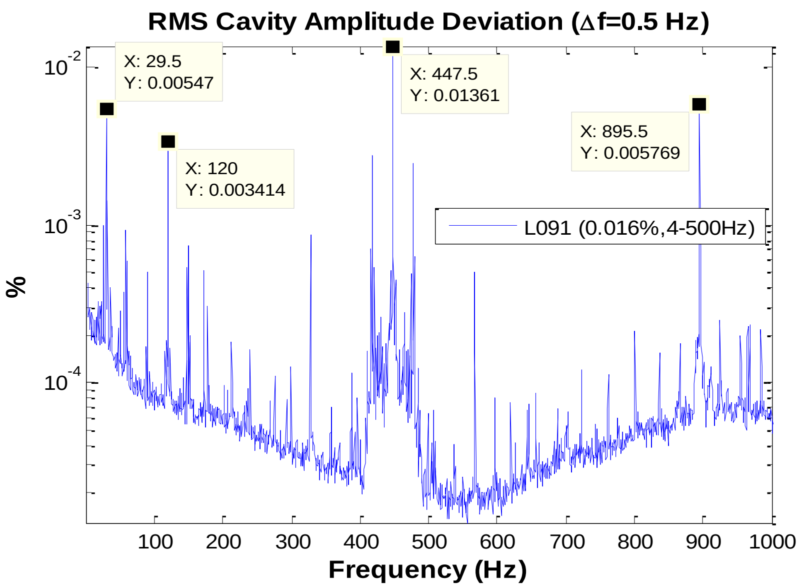


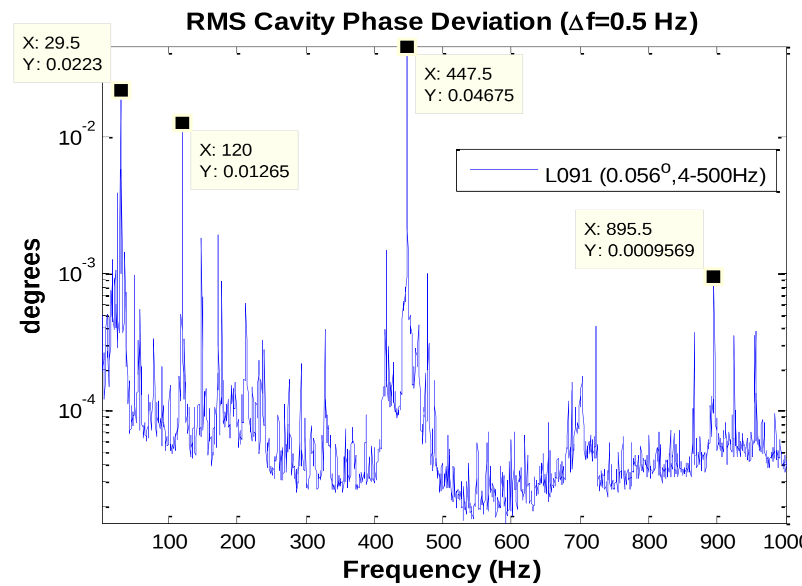
Disturbance Rejection Characteristics of the ADRC Controller





Filtered Data





Pumps		Controller				Cavities								Acceleration			
a1	a2	Amp		Phase		L077		L082		L089		L091		EW leg	NS leg	EW side	UD top
		ω_o	ω_c	ω_o	ω_c	Amp	Phase	Amp	Phase	Amp	Phase	Amp	Phase				
ON	ON	3000	600	3000	600	0.057	0.076	0.023	0.079	0.011	0.024	0.041	0.17	13	101	756	102
ON	ON	10000	5000	10000	5000	0.021	0.013	0.0045	0.017	0.0032	0.0061	0.013	0.062	13	106	692	116
OFF	OFF	3000	600	3000	600	0.074	0.09	0.0054	0.023	0.0039	0.008	0.0027	0.01	3.8	21.4	5.2	10.2

References

[1] F. Goforth *et al.*, "A novel practical control approach for rate independent hysteretic systems," *ISA Transactions*, vol. 51, pp. 477-484, 2012.

[2] J. Han, "From PID to active disturbance rejection control," *Industrial Electronics, IEEE Transactions on*, vol. 56, no. 3, pp. 900-906, 2009.

[3] J. Vincent *et al.*, "On active disturbance rejection based control design for superconducting RF cavities," *Nuclear Instruments and Methods in Physics Research A*, vol. 643, pp. 11-16, 2011.

[4] S. Zhao, "LLRF control for superconducting RF cavities," internal research report, National Superconducting Cyclotron Laboratory, 2011, unpublished.

[5] S. Zhao *et* al., "Fixed-point implementation of active disturbance rejection control for superconducting radio frequency cavities," *American Control Conference*, pp. 2699-2704, 2013.

[6] Z. Zheng *et al.*, "ADRC control for beam loading and microphonics," *LINAC 2012*, pp. 615-617, 2012.

[7] Z. Zheng *et al.*, "Piezo-electric tuner study for SRF cavity," *PAC 2013*, to be presented, 2013.

Questions

Thanks for your attention!